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EtherCAT-integrated processing machine with full local task redundancy

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Abstract

A numerically controlled processing machine, integrated over EtherCAT with full local redundancy in the axes- to task-space mapping has been designed and built in a laboratory. The redundancy arises from a set of slow, long-ranging base axes manipulating a set of fast, short-ranging tool axes, which again holds and manipulates the tool. The principle of the machine is time-efficient in manufacturing applications with high task detail and where the tool process is faster than the long-ranging axes. This paper will give an overview of construction of the machine and experimental trajectory planning.

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Keywords: EtherCAT, Machine building, Trajectory generation, Machining

1. Introduction

For reasons of simplicity and costs, manufacturing machines involving motion mostly have the number of axes matching the dimensionality of the tasks for which the machine was designed. E.g. most articulated robots perform tasks relating to rigid bodies in Euclidean space, which is a space of six degrees of freedom. Hence most articulated robots have six axes, exactly enabling them to freely pose their end-effector at any position and orientation within their workspace envelope. Some robots, however, are specialized on working with pick-and-place operations of work-pieces on a flat surface, such as a table. In "table-top" manipulation tasks, the work-pieces have two rotational degrees of freedom removed, and these specialized articulated robots, generally referred to as SCARA robots, thus have four independent axes, allowing them to pick, lift, orientate, and place work-pieces freely among planes that are co-linear with the robot base. In even simpler tasks where the last rotational freedom is fixed or irrelevant, e.g. chemical laboratory beaker filling or sampling, Cartesian robots are utilized having only the three linear spatial directions as independent axes.

A processing task may be characterized by its inherent dimensionality. E.g. simple arc-welding and milling are of inherent task-dimensionality five since, task-wise, the roll around the tool is of no significance; in milling, of course, the *rate* of this tool-roll is of high significance.

Machine or robot axes in surplus with respect to the task dimensionality may be utilized in various ways. Example aspects of utilization are: Bandwidth and dynamic differences among the axes, force and torque distribution from task and through the machine axes, energy saving, reach differences among the axes, difference in controllability among the axes in real-time, task velocity discontinuity mitigation in machine axes, and obstacle and joint limit avoidance of the mechanism.

Our utilization of the redundant axes system is covered by an aspect that may be described as the coordinated control of short-ranging, fast tool axes and long-ranging, slow base axes, where both sets of axes have locally full task dimensionality. The challenge is to find a method for decomposing the task motion into base and tool axes motion, for which we present a simple trajectory planning strategy.

1.1. Related work

The problem domain underlying this paper is well described by Cutler et al. [1]. They specify principles and methods for controlling redundant tooling machines with different dynamic characteristics among the axes.

Regaard *et al.* [2] developed a welding tool head with seam tracking for robotic laser welding. Here the robot acts as the base axes which carries the tool head through a nominal seam trajectory. The melt pool and variations in the geometry and groove are observed and identified in real-time by a laser scanner. By using a simple geometric model, the identified errors are used to offset-correct the welding process by real-time control of a lateral scanner on the welding laser. The utilized re-

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dundant axis in this case is the lateral scanner controlling the welding laser. A real-time controllable robot may replace the need of the welding laser scanner, but the emphasis is on making a robot-independent tool system that may be carried by any robot, or, more generally, any set of base axes.

Ku [3] developed a high-bandwidth, three-axis tool head for turning of very brittle material. Machining of brittle materials requires precisely controlled depth of cut at low feed rates to remain within the ductile regime. This is not easily obtained with the standard machine controller, even when it has adequate axis dimensionality for the task.

Chiu [4] explains about how task and axis spaces are coupled with respect to velocities and forces. This may be used with the redundancy of the axis space to design the motion for solving the task, and optimizing various objectives. A systematic way of setting up an index is explained, for obtaining optimal posing of the mechanism for a given task and with respect to a certain optimization regard.

2. Machine construction

For experimenting with the division into fast and slow axes of a tooling machine, a machine with two sets of axes systems has been prototyped in our laboratory. The base axes is a standard Cartesian manipulator, a type which can be supplied by many machine suppliers. Alternatively a standard industrial robot of suitable reach could be used as the base axes system. The most important requirements to the base axes system are to be able to sustain the static and dynamic load of the combined tool and tool axes system, to provide suitable reach to cover the addressed tasks, and to be able to obtain speeds that allow for acceptable processing times.

One property that is not required of the base axes is that of high acceleration. In mechanical systems the obtainable acceleration is often the limiting factor for application performance. Being able to relieve the requirement for high acceleration makes the machine design easier and the costs lower, since it greatly expands the selection of usable hardware.

The tool axes system, on the other hand, is required to obtain a very high acceleration of the tool point. Having the base axes fulfilling the application's need for reach, the tool axes system is allowed for having only short reach capability in its position control of the tool. Further, the tool axes system is only required to carry the weight of the tool and stand the load of the forces on the tool. Examples of such short-range, fast axes are piezoelectric drives, linear or direct drive motor drives, and galvanometer-actuated mirror deflectors of radiation beams. We have used a two-mirror galvanometer scan-head in the prototype machine.

2.1. Electromechanical setup

The machine set up in our laboratory consists of a Cartesian manipulator functioning as base axes system and a two-mirror galvanometer scanner functioning as tool axes. A visible laser has been mounted to serve as a harmless tool point for inspection of the trajectories executed. A camera is mounted for observing the tool point on the work-piece, playing a role in both calibration and performance observation. The current camera is of low grade and only useful for rough calibration tasks. This basic five-axes construction is usable within several contactless laser application areas, e.g. machining or cutting.

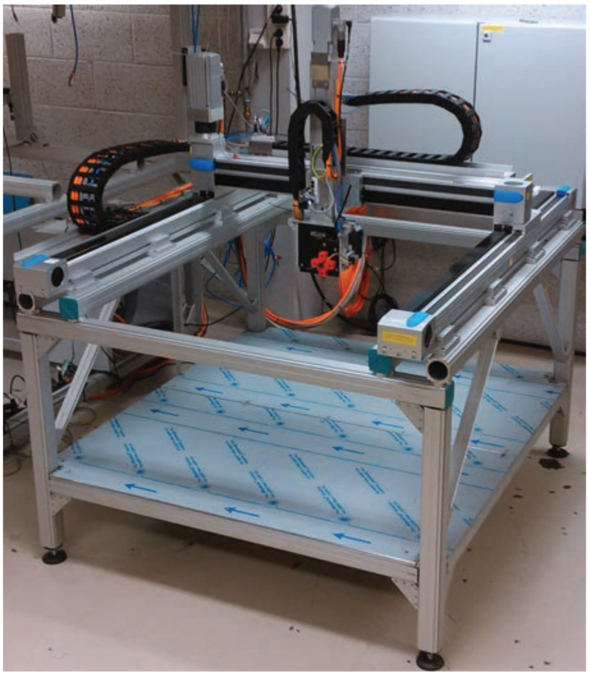

Fig. 1. Machine for testing set up in the laboratory. Three linear axes control the 3D position of a galvanometer-based laser scan-head. A visible laser is mounted with the galvanometer scanner for visual inspection of the executed task.

Figure 1 shows the prototype machine that has been set up in the laboratory. The rig is composed of Montech profiles.

The base axes system is made up of a Festo 3D gantry with belts along the horizontal axes ($\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ directions) and screw-ball along the vertical axis ($\hat{\mathbf{z}}$ direction). The operational range of the axes are 1200 mm, 800 mm, and 300 mm, respectively.

The base axes are driven by Festo EMMS-AS servo motors. The motors have different loads in the serially coupled axes system and are of appropriately dimensioned models:

- $\hat{\mathbf{x}}$- and $\hat{\mathbf{y}}$-motor: EMMS-AS-100-M-HS-RS
- $\hat{\mathbf{z}}$-motor: EMMS-AS-70-S-LS-RSB

All base directions are capable of obtaining a precision in the order of 0.2 mm. The base system is able to obtain an acceleration in the order of $10\,\mathrm{m\,s^{-2}}$ and hold a speed at a maximum of $1\,\mathrm{m\,s^{-1}}$ in the $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ directions; the principal task directions.

The tool axes system in the prototype machine is made up by a low-cost Mactron galvanometer scanner. It operates two mirrors to deflect an input beam between its input and output apertures. Each galvanometer-controlled mirror is able to rotate a range of some -0.35 rad to 0.35 rad[1] at a rate in the order of $100\,\mathrm{rad\,s^{-1}}$. At a reference operating height in the order of 0.1 m the obtainable processing speed of the tool axes system alone is in the order of $10\,\mathrm{m\,s^{-1}}$; an order of magnitude in excess of the base axes system maximum speed. Most importantly, the

[1] $-20°$ to $20°$

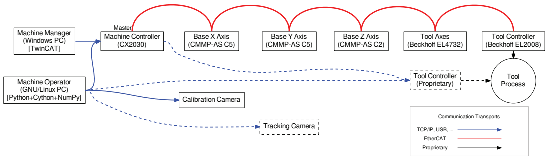

Fig. 2. Topology of major communicative components of the machine. Current prototype elements are shown with full lines, and planned and optional elements are shown with dashed lines.

galvanometer operated mirrors can accelerate beyond the order of $1 \times 10^4\,\mathrm{rad\,s^{-2}}$. This acceleration will, again at a reference operating height in the order of 0.1 m from the work-piece, result in a tool point acceleration in the order of $1000\,\mathrm{m\,s^{-2}}$; three orders of magnitude beyond that of the base axes system.

2.2. Machine control components

Figure 2 illustrates the high level topology of the communicating nodes in the machine system. Notably the EtherCAT bus, with its connections shown in red, and the EtherCAT nodes are what make up the components of the machine. EtherCAT is a field bus standardized under IEC [5]. One of the main advantages of EtherCAT is that it is an open standard meaning that both slave and master stack implementations are amply available. Another consequence of the openness is that many device manufacturers provide devices with EtherCAT slave interface. EtherCAT further provides good real-time performance with high throughput, and it does so over highly available Ethernet hardware.

The machine EtherCAT bus is led by the machine controller which provides control and management interfaces to the machine. Central to the setup are one or more base and tool axes controllers on the EtherCAT bus. The current setup has three base axis controllers, one for each Cartesian direction, and one tool axes controller for the galvanometer scanner mirrors.

External to the machine are various other systems: Machine manager, trajectory generator, calibration and tracking cameras, and proprietary tool control system.

The tool control may be performed by a node on the EtherCAT bus in the machine, but the tooling system for a pertinent application may have a proprietary controller which does not provide an EtherCAT interface. In such a case the tool control system must be operated by the machine controller for best synchronization or, more flexibly, directly from the trajectory generator if hard synchronization with the motion is not required. The current prototype setup uses a digital output line, from a Beckhoff EL2008 digital output module on the EtherCAT bus, to operate a visible, low-power laser pointer device. The tool state space is binary, for on-off control of the laser pointer.

The Mactron galvanometer scanner, used for tool axes system, is controlled by one two-channel $-10\,\mathrm{V}$ to $10\,\mathrm{V}$ analogue output unit over EtherCAT. The particular unit used is a Beckhoff EL4732 capable of delivering 16 bit resolution samples on both channels at a cycle time of down to $10\,\mu\mathrm{s}$. It is further capable of oversampling, reducing the rate of EtherCAT telegrams necessary for providing the maximum temporal resolution. Since the base axes system we use operate at a cycle time of 1 ms we aim at the same EtherCAT cycle time for the galvanometer scanner. Aiming also at a sufficiently fine galvanometer cycle time of $100\,\mu\mathrm{s}$ leads us to configure the EL4732 module at 1 ms bus cycle time and 10 times oversampling on each channel.

The Cartesian base axes system, made up of the Festo rig with Festo servo motors, is controlled by EtherCAT-enabled Festo motor controllers from the CMMP-AS series. The $\hat{\mathbf{x}}$- and $\hat{\mathbf{y}}$-axes carry the greater load, and the servos are each driven by a CMMP-AS-C5-11A-P3-M3 controller. The lighter loaded $\hat{\mathbf{z}}$-axis is driven by a CMMP-AS-C2-3A-M3 controller. The servo controllers are individually controlled in direct positioning mode at a cycle time of 1 ms using the “CAN over EtherCAT” protocol.

The machine controller feeding all controls to the devices over the EtherCAT bus is a Beckhoff CPU module of type CX2030. It serves as the EtherCAT master for the component devices, and provides external communication by two Ethernet interfaces. The Ethernet interfaces are used for management and trajectory feeding.

2.3. Management and operation

The machine system comprises, besides the machine and its internal component nodes, also a management node and an operation node. Both system nodes access the machine via the machine controller. The management node addresses the setting up of the machine controller. Mainly this consists in deploying an on-line configured system on the machine controller such that the machine controller will control the machine devices and provide an operation interface. The operation node is where the application that is to realize manufacturing tasks is deployed. The node provides resources for the manufacturing task application to execute its tasks on the machine.

The main reason for distinguishing between management and operation nodes is that the operation interface may be kept extremely simple, once a good management system is in place with an adequately deployed machine control. This relieves the operation node, and manufacturing task application, from dealing with unnecessary machine specifics. Further, as in our case, the optimal or desired operating system platforms for machine management and manufacturing task application need not coincide for all setups.

2.3.1. Machine management

Machine management is performed by an application set up with TwinCAT 3 from Beckhoff. TwinCAT is an integrated development environment, allowing for modelling a system of devices and implementing an application controlling the system. As part of the system model a central aspect is parameterizing the devices in the system such that they will be initialized correctly and operate according to the desired mode and performance.

The TwinCAT model set up for our machine simply parameterizes the motor controllers and the analogue output module controlling the galvanometers in the scanner according to the above descriptions and timings. In addition the motor controllers are calibrated and modelled as NC-axes making it easy for the machine control application to control them.

According to the setup sketched in the previous sections, the application needs to clock the EtherCAT bus every 1 ms with a new set of control targets to all devices. The EtherCAT standard

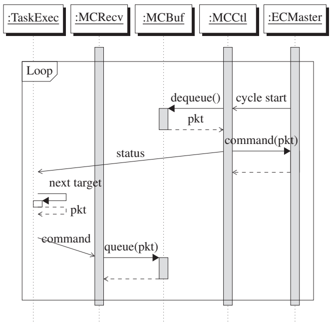

Fig. 3. Sequence of calls and messages between the machine controller, the task system and the EtherCAT bus master.

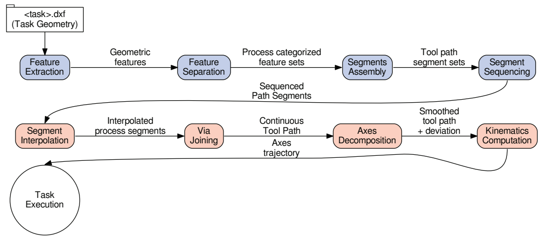

Fig. 4. The two sub-processes of task perception, shown in blue, and trajectory planning, shown in red, illustrated by their sequences of operations. The generated trajectory is fed to the sub-process task execution.

allows for the slave devices having different update rates, but we have settled on one common update rate for simplicity of the operational interface.

2.3.2. *Machine operation*

The operation of the machine is considered as what takes place in the machine controller during interaction with a client task system deployed on the machine operator node; see Figure 2. The task system must assume responsibility for maintaining a soft real-time 1 ms-cycle of feeding new, valid state commands to a motion buffer in the machine controller. The machine controller will operate according to the buffered targets as long as there are targets in the buffer. An under-run of the motion buffer will make the machine controller slow down safely to a stand-still, where it will remain until there are again valid targets in the motion buffer.

The current operation interface uses UDP for communicating the status and command packets between the machine controller and the task system. The interface logic is illustrated in Figure 3. The operation cycle is started by the EtherCAT bus clock, when it is time to feed new target states to the machine components. The machine controller de-queues a command state from the motion buffer, and simultaneously sends it to an external task system as an UDP packet and to the EtherCAT bus. This should trigger the computation of a new command target in the task system, which will then be sent to the receiver in the machine controller. The receiver queues the new data packet in the motion buffer.

Using UDP will allow high throughput, low latency, and clean packet separation over the Ethernet connection, at the cost of reliability and transmission error detection. However, when using a dedicated cable between dedicated network cards at both ends, the error rate is not affected by packet collisions on the network, and the error rate falls back to lower level errors. This has been working stably and reliably enough for many hours of prototype system operation. Transmission loss is easily discovered at the application level at both ends, since the communication is periodic and two-way. Transmission errors may be fairly easily detected by command and status packet inspection and state tracking. Though using TCP for the connection would implicitly implement some of these steps, it would not be able to deal with the error handling and correction in any case.

The command and status data packets contains the raw parameter state of each device. Each base servo will be described by its position, velocity, and acceleration, each of which are represented by a 64 bit floating point value. The analogue output module has a state of ten 16 bit integers for each galvanometer in the scanner. The current implementation allows for 64 bit of tool control information, of which currently only 1 bit is used for having the visible laser on or off.

The motion buffer in the machine controller ensures that jitter over the Ethernet communication does not make the machine controller miss deadlines on the EtherCAT bus. The cost of thus stabilizing the Ethernet communication towards the hard real-time EtherCAT bus is that there will be a slight execution delay between the task system and the machine components. Good operating systems and software platforms in both ends of the Ethernet communication should ensure that the buffer need not be larger than a few packets. If the Ethernet connection is not run over a direct cable, but runs through one or more switches, the buffer level may need to be increased.

The sending of status packets and reception of command packets in the machine controller take place asynchronously. The status packets will contain information about the motion buffer level, such that the task system may speed up the emission of command packets to avoid under-run in the motion buffer. The status packets will further be used for initialization and tracking of the machine state in the task system.

3. Task system

This section addresses the combined activities of perceiving a manufacturing task, planning the trajectory for executing the task on a machine, and executing it on the machine. In short, we call the software system performing these activities the *task system*, as distinguished from the machine system. In the current work we implemented a simple, integrated task system for experimental purposes. A representation of the activities in the implemented task system is shown in Figure 4

3.1. *Perception, planning and execution*

The important concepts of the task system in our ontology are thus *task perception*, *trajectory planning*, and *task execution*. These activities are not temporally separable in general but need, under certain circumstances, to proceed in an iterative or simultaneous manner; i.e. on-line or real-time[2], respectively. However, for the simplest types of tasks with well-shaped workpiece geometry and well-calibrated machines, the task perception and trajectory planning may be performed in an off-line manner, after which task execution simply feeds the generated trajectory in a timely manner to the machine controller.

Task execution in the simple case was adequately described in Section 2.3.2. Task perception comprises the process steps in Figure 4 from *Feature Extraction* to the operation *Segment Sequencing*. The details of task perception is highly application-domain dependent and will not be treated further here.

This section is focusing on trajectory planning, which is of a more generic nature with respect to the application-domain. Trajectory planning is the aspect of the task system that works out a motion plan and generates a feasible trajectory for the pertinent machine which solves the pertinent, perceived task. When advanced tooling and tool process planning is involved, trajectory generation can not be dealt with in as simple geometric terms as we present here. For the sake of prototype experiments, we restrict the trajectory planning to deal with only geometric problems, and with the tool process aspect only represented by some preset tool speeds and tool on-off control.

3.2. Trajectory planning

Referring to Figure 4, the operations that are performed by the trajectory planner are sketched in the following.

An ordered sequence of segments of geometric features is the output from the task perception process. These are *segment interpolated* to the finest level given by the process specification; e.g. process tool speed. This will become a tool trajectory that matches the process features given in the task description.

The spatial gaps between process segments remain at this point. To obtain a trajectory which could in principle be executed, the segments are *via joined*. Since each gap between segments already have an entry and exit velocity, cubic Hermite interpolation is very intuitive to use and yields continuous velocities on the via- and process-trajectory transitions. This leaves us with a complete, continuous tool trajectory. Note that most task descriptions, in geometric terms, do not provide any guarantee of velocity continuity , so even if we make the via trajectories twice continuously differentiable, eliminating the discontinuities in the tool process trajectories, there will generally remain velocity discontinuities within the process trajectory segments.

Axes decomposition and *kinematic computation* are the core operations in the trajectory planning process and the most essential part of the presented work.

3.2.1. Axes decomposition

The problem presented by the continuous tool trajectory after it has been interpolated and via-joined is evident: There remain discontinuities in the velocity of the trajectory, which are insurmountable for a standard servo-based axes system; e.g. at corners in the task specification. The problem is well known in robotics [6], where blend-zones are introduced around velocity discontinuities. If entry and exit velocities at the discontinuities are sufficiently large, the size of the blend-zones will exceed the task tolerance, and the trajectory has to be re-parameterized to trace the same path but at lower speed in the vicinity of the discontinuities.

A fast tool servo system, in terms of acceleration, alleviates this problem since the blend-zones can, in principle, be extended as far as the working envelope of the tool servo system. If the base and tool servo axes trajectories are generated in a coordinated manner, this will allow for more efficient, simultaneous operation of both axes systems. The more traditional way of utilizing two axes systems is to keep one set of axes static at any time, and let the tool axes work the tool over the task patch by patch.

In practice such problems arise at any tool trajectory region where the acceleration exceeds the capacity of the base servo axes. Such regions stem from tool path features with sufficient curvature and target tool processing speed. Hence, it is desirable to strategically tackle any kind of high detail in the task features by ignoring them in the base axes system, dealing with them entirely in the tool axes system. A simple mathematical method is to consider the coordinates of the tool trajectory as signals. These coordinate signals may then be decomposed into a smooth, low-frequency part and an erratic, high-frequency part.

Such a decomposition is mathematically achieved by folding a simple normalized window function coordinate-wise over the tool trajectory; e.g. using a triangle, Hanning, or Gauss window. The only parameter of the filter window is its length, determining how much of the surrounding trajectory is to influence a given operation point. This length should naturally be comparable to, and not larger than, the size of the working envelope of the tool axes system. Such a method is presented by Delta Tau Data Systems, Inc. in their application note "Spectral Decomposition" [7].

The smoothed tool trajectory is then taken as the target of execution of the base-partial machine consisting of the base axes. The tool point of this partial machine should be considered the machine tool point with the tool axes at its home position. Then the tool-partial machine must solve the high-frequency part of the tool trajectory in its own home-reference system. This means running kinematic computation passes for separate base- and tool-axes over the low- and high-frequency tool trajectories, respectively.

3.2.2. Kinematic computation

A Kinematic model is an essential part in transforming a tool trajectory into an axes trajectory. A servo controller will only be able to execute a trajectory for its axis. Thus, since the task specification live in, at best, tool reference, any machine system must have a kinematic model somewhere in its planning and execution stack. More importantly, the kinematic model must be capable of computing the inverse kinematics, which is the transformation of tool poses to axes poses.

The kinematics, forward and inverse alike, of an ideal Cartesian arrangement of axes is of little challenge; i.e. if the axes are perfectly orthogonal and straight, and if the encoder system is perfectly linear. Depending on the task tolerance, this may or may not be the case in practice. Fortunately a sophisticated model that may host these imperfections is not too challenging.

[2]We consider a computational activity as strictly on-line if it does not obey system deadlines, but needs information from surrounding systems at the time of operation.

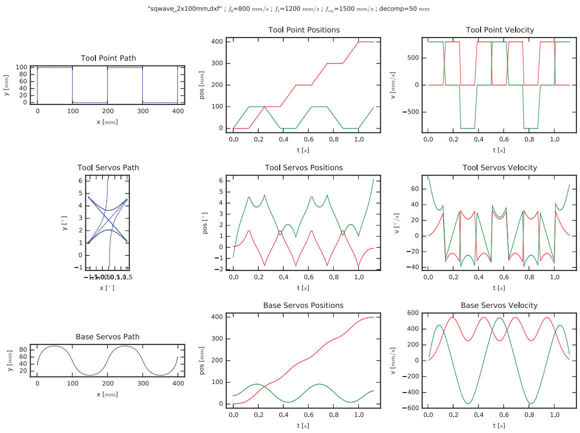

Fig. 5. Trajectory planning for a square wave task with short filter length. N.B. the interpolation level shown in the plots is not representative of the real trajectories; they have been down sampled for better illustration.

Currently a simple, direct model is used for prototype experiments.

The kinematics of a galvanometer scanner is less simple and direct, but still no problem to establish in the ideal case. However, achieving a sufficiently realistic model requires some further development and skill. See e.g. [8,9]. A realistic inverse kinematic model is indeed a challenge, but will be necessary to achieve high accuracy of the machine.

3.3. Example

To illustrate the planning method, trajectories for an example task is shown in Figure 5. The example task is a square wave tool trajectory of characteristic dimension 100 mm that is to be traced at a tool speed of $800\,\mathrm{mm\,s^{-1}}$. It is a simple example that does not illustrate via-joining, but exhibits strong velocity discontinuities at the corners. The task path is shown in the upper left-hand corner. The resulting smoothed base axes path is shown in the lower left-hand corner, and illustrates the smoothing out of the tool path to an almost sinusoidal path. The smoothness of the base axes trajectory is best observed from the axes velocities plot in the lower right-hand corner. There changes in the base axes velocities are very smooth. Another observation is that the base axes executes at a maximum of less than $600\,\mathrm{mm\,s^{-1}}$, thought the tool speed is kept constant at $800\,\mathrm{mm\,s^{-1}}$. Without smoothing and operation of the tool axes, the base axes would have followed the exact course of the tool trajectory.

The tool axes trajectory illustrated in the middle row of Figure 5 shows the erratic, but acceptable, behaviour of the tool axes system, when it has to compensate for the error between the base axes trajectory and the tool trajectory. The effect is best observed from the velocity plot of the galvanometer axes shown in the middle right-hand plot. It is evident that the velocity-discontinuities from the original tool trajectory has been carried over to the tool axes trajectory. As long as the velocity discontinuities are within the dynamic capability of the galvanometers, with respect to the task tolerance, this will be a valid trajectory for solving the task with the machine.

4. Conclusion

Up to this point of development, the machine, and notably the machine controller, operates well. It supports a flexible interface for feeding a state space trajectory in real-time. The principles on which the machine has been based seems promising and viable for flexible manufacturing purposes.

The trajectory generator is still a work in progress, but at its current level it is is capable of demonstrating the principle of axes space decomposition of a tool trajectory for solving a general, geometric task.

Kinematic modelling is based on ideal geometry in the presented work, but realistic kinematic models are currently work in progress. Dynamic effects within the machine are unmodelled in the presented work, and may turn out to have a great impact on performance; they remain yet to be examined.

The current state of the prototype system suffers from means of quantitative evaluation of the machine performance. We are currently working on installing a tooling system such that actual work-pieces can be produced. Calibration procedures are also being developed based on high-resolution imaging of the tool point. Both of these steps will allow quantitative evaluation of the machine.

5. Acknowledgements

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